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13. ABSTRACT (Maximum 200 words)

The overall objective of this MURI program was to develop a new class of lightweight armor materials in the form of layered ceramics and metal ceramic composites. This entailed developing novel processing techniques, extensive dynamic experimental evaluations and modeling as well as new analysis and experimental methods. The research program consisted of four major areas: manufacture of layered ceramics and ceramic metal composites for armor, constitutive modeling and damage mechanisms, ballistic penetration experiment and simulation, and development of advanced experimental and computational methods. Briefly, in the processing area, two versatile routes for production of layered and graded multilayer ceramics have been developed: sequential centrifugal casting and lamination of tape-cast ceramics. In the mechanics and modeling area, microstructural effects on the response and failure in heterogeneous materials under dynamic loads were studied and modeled. New experimental methods were developed with the aid of inverse methods in conjunction with the FEA. Improved computer codes for simulation of projectile penetration were achieved.

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For the period of the MURI program, 17 students have competed their PhD degrees, 15 students have earned their MS degrees, and 4 post doctoral fellows have participated in the research..

2. INTRODUCTION

The use of lightweight and damage tolerant armor materials is essential for making future U.S. Army vehicles lightweight, serviceable, and readily deployable. The Purdue-UDRI MURI research program was directed to the development and evaluation of a new class of layered and metal ceramic composites for armor applications. This entailed developing novel processing techniques, extensive dynamic experimental evaluations and modeling as well as new analysis and experimental methods. The objectives of this MURI program were thus established accordingly.

The Purdue-UDRI program started in August 1996. The research covered many areas that are closely related to the aforementioned objectives. The research effort has so far produced 51 journal papers, 42 conference papers, 54 presentations, and 1 proceedings edited. The program has also had significant educational impact: twenty four students have conducted research under the support of this grant and obtained their advanced degrees- 15 masters and 17 PhD's.

In the original proposal for the MURI grant, four major research areas were proposed including manufacture of layered ceramics and ceramic metal composites for armor, constitutive modeling and damage mechanisms, ballistic penetration experiment and simulation, and advanced experimental and computational methods. For each area, we have completed and in many cases exceeded what we envisioned in the proposal. Following is a list of topics which have been studied under this program; some of which are presented with more details in the following section ant the rest may be found in the published papers.

1) Manufacture and Properties of Layered Ceramic and Ceramic-Metal Composites
   - Centrifugal casting for making layered ceramic tiles
   - Anisotropic and nonhomogeneous hardness, fracture toughness, and residual stresses
   - Effect of controlled microstructures
   - Low pressure/spontaneous infiltration techniques for making ceramic-metal composites

- Modeling capillarity in porous media
- Tape casting of layered oxide ceramic composites
- Ballistic evaluation of under sized ceramic tiles
- Effect of contiguity on properties of co-continuous ceramic-metal composites

2) Constitutive Modeling and Damage Mechanisms
   - Viscoplasticity model for high strain rate response in polymeric composites
   - Dynamic interlaminar fracture toughness in polymeric composites
   - Modeling of co-continuous ceramic-metal composites
   - Continuum model with micro-inertia
   - Failure of brittle materials under confinements
   - Wave attenuation in layered media
   - Dynamic microcracking in ceramics using grain level model
   - Multi-plane microcracking model
   - Simulation of intersonic crack propagation in polymeric composites
3) Penetration Experiments and Simulation
   - Penetration experiments with in-situ real time measurement of tail penetrator velocity
   - Ballistic penetration with in-material stress and free surface velocity measurements
   - Modeling of confined multilayered ceramic targets against long WHA penetrators
   - Delamination of woven composites under plate impact and penetration experiments
   - Reverse ballistic experiments on undersized ceramic tiles
   - Penetration and damage tolerance of layered ceramic-metal laminates
   - Simulation of ballistic penetration in Al/Alumina targets using EPIC code
   - Interface defeat ballistic penetration
4) Advanced Experimental and Computational Methods
   - Pressure-Shear soft recovery impact experiments on fiber composites and ceramics)
   - Dynamic fracture experiments with real time measurement of loads, high speed photography of growing cracks and speckle cross-correlation for full field deformation measurement (layered ceramics and composites)
   - Compression-shear Kolsky bar for dynamic friction and dynamic torsion testing of nano-materials
   - High temperature plate impact experiments for Ti alloys and ceramics
   - New experimental methods made possible with inverse methods in conjunction with the FEA

3. HIGHLIGHTS OF MAJOR RESEARCH ACHIEVEMENTS

3.1 Processing and Properties of Layered and Graded Ceramics and Ceramic-Metal Composites

A series of novel ceramic and ceramic-metal composite processing routes have been developed under this thrust, which resulted in the production of a wide range of new materials having oriented, layered and/or graded microstructures. These materials not only enabled systematic studies of various microstructure effects on mechanical performance, but also stimulated the development of innovative properties characterization methods, most notably an *in situ* fracture resistance curve measurement technique.

Two versatile routes for production of layered and graded multilayer ceramics have been developed, sequential centrifugal casting and lamination of tape-cast ceramics. These methods have been applied to oxide, carbide, and nitride ceramics, including Al_2O_3, ZrO_2-Al_2O_3, B_4C, AlN, and Si_3N_4, with densification by sintering or liquid metal infiltration to produce ceramic-metal composites. Several fugitive phase techniques for producing ceramic preforms with tailored porosity for metal infiltration also have been demonstrated. Numerical analysis of capillarity in packed spheres provided the basis for a new low-pressure infiltration process. Quasi-static, dynamic, and ballistic fracture testing has been performed to characterize fracture behavior and residual stress effects in layered composites. Just important as the new processes, materials, and properties understanding, eight MS and/or PhD student researchers have been supported by this program. The overall research accomplishments are summarized in terms of the specific processes/materials and students who developed them.

3.1.1 Layered Al_2O_3/Al_2O_3 Composites

Erik Drewry (MS, 1998) and Joachim Brehm (Technical University of Darmstadt (TUD) visitor, 1998) developed the initial centrifugal casting of multilayer ceramics using fine alumina slurries containing a fraction of coarse tabular alumina particles. Size segregation during settling and resulting constrained densification near the larger particles created porous, coarse-grained interlayers. Specimens up to 75 mm diameter with a range of layer thickness and number were produced crack-free after developing a special binder systems and controlled drying. A series of model experiments studied the development of layer curvature and tilt, which are characteristic of radial centrifugation. SENB fracture tests across the layers resulted in extensive lateral fracture and an apparent toughness as high as twice that of dense monolithic alumina control specimens, with a strong dependence on layer thickness and interlayer porosity. A measurable effect of crack orientation relative to layer curvature direction (into or out of the curvature) was also observed, which represents a new aspect of toughening in multilayer composites. Dynamic and ballistic testing studies showed stepwise cracking of the specimen periphery and plate-like fragments demonstrating that fracture occurred along the porous interlayers, without adversely affecting ballistic performance compared to monolithic alumina.

3.1.2 Layered Al_2O_3/ZrO_2 Composites

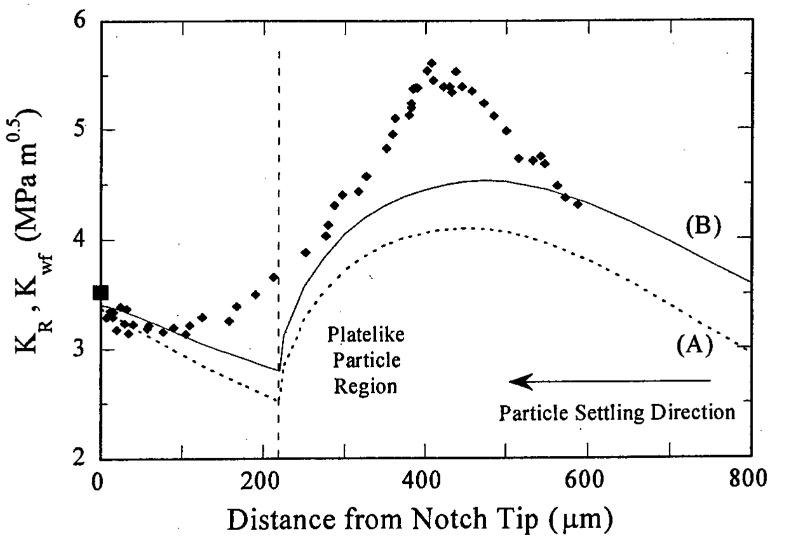
Robert Moon (PhD, 2000) completed extensive *in-situ* fracture measurements on microscale crack propagation resistance versus crack length (R-curves) in Al_2O_3-ZrO_2

multilayer composites. Rob worked closely on these measurements with Professor Jürgen Rödel, Technical University of Darmstadt, Germany. *In-situ* optical microscopy observations of crack initiation and extension were made using a four-point bend fixture mounted on an optical microscope. Both surface crack in flexure (SCF) and single edge v-notch beam (SEVNB) test methods were employed to measure fracture resistance (R-curves).

Multi-layered composites (typically 15 layers) were produced by sequential centrifugal consolidation of flocculated aqueous co-suspensions of Al_2O_3 and Ce-Al_2O_3. Bend test specimens were v-notched using a razor blade technique, producing notch tip radii consistently less than 10 μm. The SEVNB test method enabled positioning of the v-notch tip within a layer and the short crack extensions (5-10 μm), allowing the influence of specific microstructure features on K_{IC} to be measured directly. Figure 1 shows one of many *in-situ* SEVNB fracture results. This particular type of Al_2O_3-ZrO_2 composite contained 5 vol.% coarse Al_2O_3 platelet additions resulting in steep grain size gradients at the layer interfaces, with comparatively shallow Al_2O_3-ZrO_2 gradients across the layers. The v-notch was positioned near the center of a layer, from which the crack was propagated in the opposite direction of particle settling.

The measured fracture resistance rises steeply near the interface, reaching a maximum at a depth of ~400 μm into the adjoining layer and then decreases. The proposed mechanism of toughening is large grain bridging. Superimposed on Fig. 1 are fracture toughness curves predicted using weight function analyses with and without consideration of large grain bridging effects. The steeply rising toughness is predicted well, as is the position of the maximum toughness.

In addition to the *in-situ* static fracture studies, over 30 specimens with various Al_2O_3-ZrO_2 multilayer microstructures were produced for dynamic fracture studies by Espinosa (NWU), as well as ballistic testing (Brar, UDRI).



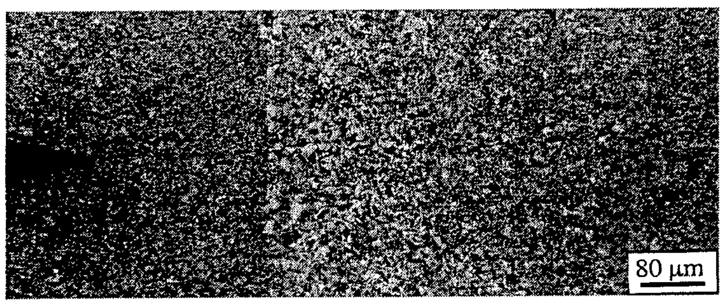


Figure 1. R-curve measured by *in-situ* SEVNB on Al_2O_3-ZrO_2 multilayer composite containing coarse alumina additions and corresponding specimen microstructure. Crack propagation across the layer interface from fine-grain to coarse-grain regions (i.e., opposite the particle settling direction) resulted in steeply rising fracture resistance. Superimposed are two toughness curves that were predicted by weight function analyses: (A) not including large grain bridging and (B) including bridging stresses.

3.1.3 Layered Oriented Si_3N_4

Will Blanton (MS, 1999; PhD, current student) has produced multilayer, oriented Si_3N_4 by laminating tape-cast layers. Although Si_3N_4 is well known for high fracture toughness arising from elongated grain structures, it has received little attention as an armor ceramic. By aligning beta-Si_3N_4 seeds in the tape during casting, laminating the tapes and hot-pressing, the strong anisotropy in Si_3N_4 can be tailored to produce damage tolerant multilayers with elongated grains in the plane. One architecture involves misorientation of the aligned grains from layer to layer, with the goal of frustrating transverse crack propagation.

3.1.4 Infiltration Capillarity Modeling

A wide range of new ceramic-metal composite microstructures have been achieved using infiltration processing. In support of this work, capillarity modeling was conducted by Jon Hilden (PhD, 2001) using Surface Evolver numerical software. Analysis of model pore structures defined by close-packed spheres have provided the first geometry-explicit

solutions for the capillary pressure as a function of surface tension, contact angle, particle size and degree of infiltration. The meniscus profiles develop anticlastic curvature and the analysis captures the formation of pendular rings, a well-known phenomenon responsible for hysteresis in infiltration/drainage experiments.

3.1.5 Damage-Tolerant Oxide-Aluminum Composites

Rick Cichocki, Jr. (PhD, August 2000) developed several fugitive phase processes for producing alumina preforms having tailored porosity for metal infiltration. One process involves producing a gradient porosity structure by colloidal alumina infiltration of compression molded polyurethane foams. The foam is then pyrolyzed and the ceramic fired, leaving the negative pore structure, which can be graded in volume fraction by spatially varying the degrees of foam compression. Using wax spheres to create large metal phases and similar size spray-dried alumina granules, alumina-aluminum composites were produced having essentially identical phase volume fractions, but opposite metal-ceramic continuity (Fig. 2). Bend testing showed relatively high damage tolerance for the metal matrix version, despite the high ceramic volumefraction (~50%). Fractography revealed a new mechanism of damage tolerance involving distributed cracking of the coarser alumina granules.

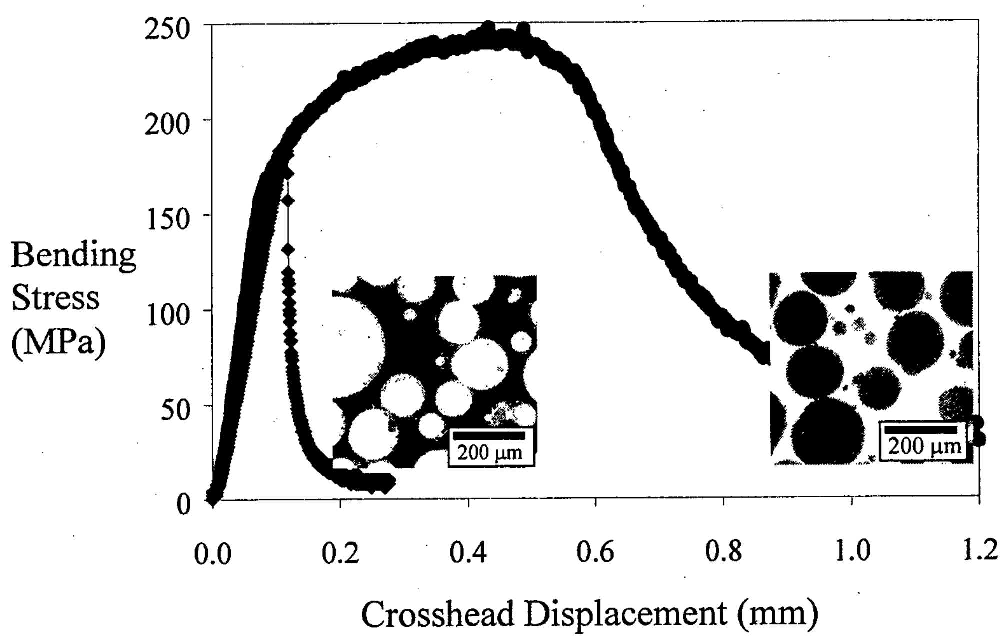


Figure 2. Bend test results for alumina-aluminum composites containing approximately equal phase volume fractions, but inverse phase continuity. Composite having alumina spheres in continuous aluminum matrix (right) exhibits much higher toughness due to distributed damage via subcritical cracking through larger alumina granules.

David Heemstra (MS, 2001) demonstrated even higher toughness in bending for similar volume fraction Y-ZrO_2 granule-aluminum composites produced by low-pressure infiltration. This process achieves infiltration in a conventional vacuum furnace by melting the metal atop the preform under vacuum and simply venting the furnace to atmospheric pressure or slightly higher. Bend testing of 3Y-ZrO_2 (partially stabilized, transformation toughened), revealed even higher ductility than for the analogous alumina-aluminum composites with approximately the same strength.

3.1.6 Ultralight AlN-Al and B_4C-Al multilayer composites

Will Blanton (MS, 1999) developed a perform treatment process enabling the production of AlN-Al composites by low-pressure infiltration, significantly shortening the processing time necessary in this system. Although layer delamination problems in drying prohibited the production of large multilayer AlN-Al composites by centrifugal casting, microhardness depended more strongly on ceramic phase contiguity than volume fraction.

Fuhong Zhang (PhD student) developed the centrifugal casting preform route to produce multilayer, graded B_4C-Al composites by spontaneous infiltration. SEVNB (v-notched using razor blade technique described above) fracture toughness measurements yielded an average toughness of 7 MPa$\sqrt{m}$ across the layers. In addition to extending this system into preforms made by laminating tape-cast B_4C, Fuhong developed an innovative solution to the challenging problem of high chemical reactivity between B_4C and molten Al. Utilizing a barrier layer of coarse alumina granules in the low-pressure infiltration process, contact is delayed until the temperature is sufficient (~1200°C) to produce an oxide-free aluminum surface under vacuum. The reduced infiltration temperature and contact time virtually eliminate reaction products in this important system.

3.1.7 Ballistic Evaluation

a) Shock and Ballistic Response of Purdue Layered Alumina and Alumina/Zirconia Composites

Ballistic performance of the 5-6 mm thick and about 60 mm in diameter ceramic composite disks against 0.3-inch diameter hardened (Rc=62) tool steel penetrators (L/D=5, mass=14.7 g) shot at 915 m/s was evaluated. The composite disks fitted in holes in stainless steel rings (OD=150 mm) were glued on top of 150 mm long 6061-T6 aluminum cylinders. The DOP of the penetrator in aluminum below the composite compared with DOP in aluminum without any ceramic provided the ballistic efficiency data. These data compared with those obtained using monolithic 99.5% (CAP III) Cercom alumina suggest that ballistic efficiency of 5 mm thick composite is comparable to Cercom alumina. However, ballistic efficiency of 6.4 mm thick composite is roughly half of that for Cercom alumina. Numerical simulation (EPIC2D) of the ballistic penetration in aluminum below alumina in all cases agrees reasonably well with measurements.

b) Ballistic Penetration Resistance of Purdue Composites

We determined penetration resistances, R_t, of basal armor and those of targets with composite and CAP III alumina disks using the following modified Bernoulli's law

$$R_t = Y_p + \tfrac{1}{2}\,\rho_p\,(V-u)^2 - \tfrac{1}{2}\,\rho_t\,u^2$$

Where Y_p, ρ_p, and V are the yield stress, density, and strike velocity of the penetrator, respectively, and ρ_t is the target density. Penetration velocity, u, in the ceramic disk is estimated by assuming that the penetration into the basal armor is proportional to the residual penetrator length and is given by

$$u = V / [1 + (L (1 - P_r/P_\infty)/T_c)]$$

$$u = \frac{V}{1 + \frac{L[1 - P_r / P_\infty]}{T_c}}$$

Where L, P_r, and P_∞ are the penetrator length, DOP in basal armor with ceramic disk on top, and DOP in basal armor without any ceramic, respectively, and T_c is the thickness of the ceramic disk . Penetration resistance values for different targets, summarized in Table 1, show that R_t for alumina composite is approximately the same as that for CAP III alumina. Further ballistic investigations are planed, as more composite specimens become available.

Table 1. Ballistic Performance of Purdue (Composite) Alumina (PA) and Coors CAP III Alumina (CA) Disks

Shot No.	Ceramic/Thickness (mm)	Penetrator Velocity (m/s)	Yaw, Pitch (°)	DOP (mm)	Target Resistance (GPa)
6-3396	No Ceramic	865	NA	58.2	1.6
6-3397	No Ceramic	916	NA	66.0	1.6
6-3398	PA/6.35	900	1 (D), 1 (L)	18.0	4.0
6-3399	CA/6.35	911	0.5 (U), 1 (R)	12.4	4.2
6-3400	CA/6.35	921	0, 1.5 (R)	9.8	4.3
6-3401	PA/6.35	911	0.5 (D), 0.5 (L)	18.8	4.1
6-3402	PA/5.0	921	0, 2 (R)	34.7	3.9
6-3403	PA/5.0	916	0.5 (D), 0	32.2	4.0
6-3404	CA/5.0	915	0, 0.5 (R)	33.9	3.9
6-3405	CA/5.0	913	0.0.5 (R)	27.4	4.1

c) Ballistic Evaluation of Undersized Purdue Alumina/ Zirconia Ceramics

Robert Moon, graduate student at Purdue, attempted to fabricate 60-mm diameter graded density alumina and alumina/zirconia ceramic disks for us to compare their ballistic performance to monolithic AD-995 alumina. The ceramic disks developed some cracks on the periphery and surfaces during the sintering process. In order to obtain crack free ceramics for the ballistic evaluation he had to reduce the size to squares measuring about 35-mm on edge and 5.7-mm thick. The standard 30-caliber APM2 projectile is

oversized for these ceramics. We designed reverse ballistic tests, in which the ceramic is glued on top of a 50-mm diameter 6061-T6 aluminum cylindrical projectile. The projectile is launched in a 50-mm powder gun at 1100 m/s against a 3-mm diameter, L/D 10 and 15, hemispherical nose tool steel rod held parallel to the barrel axis in the target tank. Penetration depth (DOP) of the tool steel rod in aluminum below the ceramic was determined using a pair of orthogonal flash x-rays. These tests are extremely violent in that the gun blast partially damages the x-ray cassette holders and other fixtures in the target tank. Measured DOP in Purdue ceramic tiles was compared to that in monolithic alumina ceramic tiles. In the case of monolithic alumina measured and numerically simulated DOP determined using Simha's model for AD-995 agreed within 5%.

3.2 Modeling of Heterogeneous Solids

3.2.1 Metal-Ceramic Composites

Ceramic metal composites have been investigated as materials with potentially high toughness and damage tolerance. Many of these materials are co-continuous and require different considerations in modeling.

In this study, co-continuous ceramic metal composites were processed, using infiltration of alumina preform. Figures 3 and 4 shows the micrographs of the co-continuous metal ceramic composites. The dark phase indicates alumina and the lighter phase indicates metal. These composite materials were processed by metal infiltration into alumina perform in a high temperature furnace. In these composites, both constituent phases are continuous. From Figures 3 and 4, the contiguity indexes were obtained to be 0.48 and 0.26 for two composites, respectively. Note that these contiguity indexes represent the contiguity of alumina phase in the copper/alumina composite, and the contiguity of aluminum phase in the aluminum/alumina composite.

A two-layer model and a new micromechanical model were introduced to predict stiffness and nonlinear behavior. Thermo-mechanical analysis was performed to predict thermal residual stresses resulting from CTE mismatch between the ceramic phase and the metal phase. It was found that the contiguity, as well as volume fraction, plays an important role in characterizing mechanical behavior of co-continuous composites.

In order to account for the 3D nature of the composite, a new 3D micromechanical model as shown in Figure 5 was adopted in the FEM analysis using ABAQUS. Note that the connectivity of both phases is ensured in all three directions. The contiguity of the micromechanical model is calculated as the ratio of the cross sectional area of the connecting rods to surface area of the spheres.

Figure 6 shows the thermo-mechanical analysis results. The predicted thermal residual stresses resulting CTE mismatch between two phases are compared to measurements. For the copper/alumina composite, the increment of thermal residual stresses is about 45% from contiguity of 0.1 to contiguity of 0.5. Thermal residual stress decreases by 15%, according to the increment of the contiguity of metal phase, for the aluminum/alumina composite. Figure 7 shows FEA prediction of the stress-strain curve for the copper/alumina composite. To include the effect of thermal residual stresses, the mechanical loading is applied after the thermal loading. It is obvious that the contiguity, as well as volume fraction, affects the mechanical behavior of co-continuous composite materials in the nonlinear region, while its effect on elastic properties is relatively small.

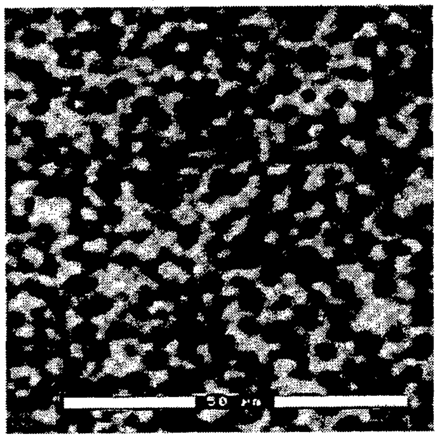


Figure 3. SEM image of copper/alumina composite at 2300x magnification

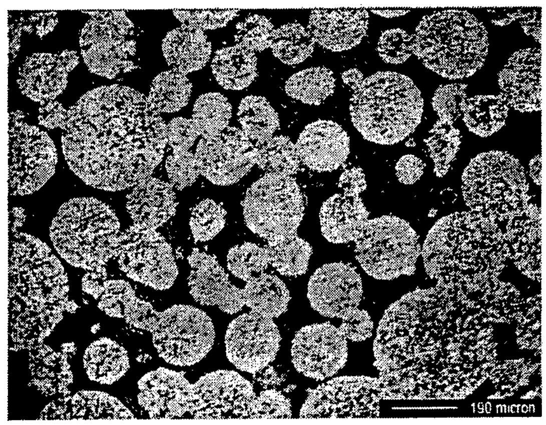


Figure 4. Optical micrograph of aluminum/alumina composite at 100x magnification

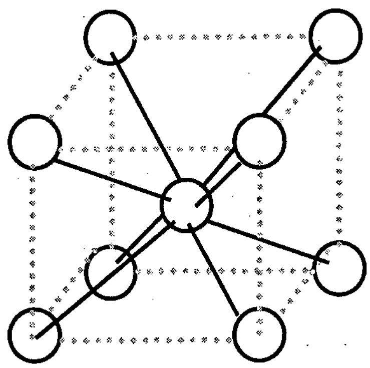


Figure 5. Schematic diagram of micromechanical model of co-continuous composite

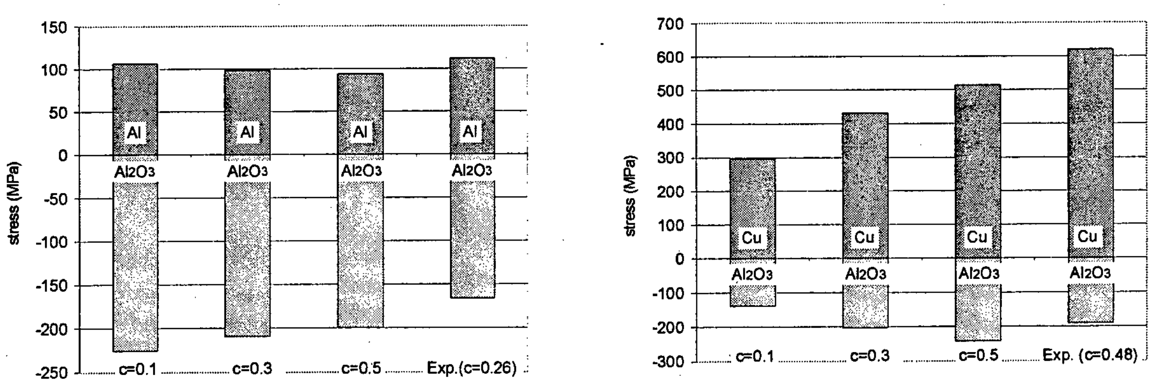


Figure 6. Thermal residual stresses for different contiguities. (a) copper/alumina composite: alumina volume fraction=68% and contiguity=0.1, 0.3, 0.5. (b) aluminum/alumina composite: alumina volume fraction=30% and contiguity=0.1, 0.3, 0.5

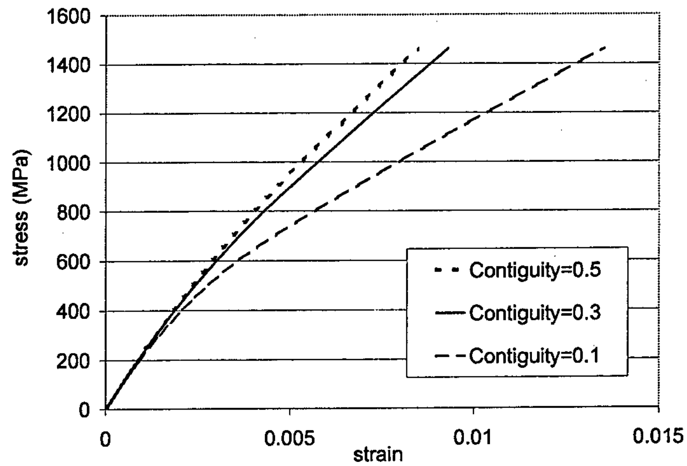


Figure 7. Stress-strain curve of copper/alumina composite obtained from FEA. alumina volume fraction=68% contiguity=0.1,0.3,0.5

3.2.3 A Micro-inertia Model for Shock Loading

Classical continuum model cannot be used to describe the dynamic response of heterogeneous solids when loading rates are high because the inertia of the local motion is not accounted for in the model. In this study, a continuum model including micro-inertia for heterogeneous materials is developed using the micromechanics method. The macro-strain and stress are defined as the volume averages of the strain and stress fields in the representative volume element (RVE). The macro equation of motion is derived by Hamilton variational principle in which the strain energy density and kinetic energy density involve the micro-inertia terms.

The new macro equations of motion have the following form

$$\frac{\partial \Sigma_{ij}}{\partial X_j} + F_i = \bar{\rho} \ddot{U}_i$$

where Σ_{ij} is the macro stress, X_j is the macro coordinate, $\bar{\rho}$ is the average density, U_i is the macro displacement, and F_i is an effective body force which is caused by micro inertia. The effective body force is determined by approximate local displacement field in the RVE and has a simple form. It is important that the local stress field can be recovered from the macro stresses. A recovery method has been developed to obtain the local stress field from the average stress field.

The proposed model was used to study wave propagation in layered media. Figure 8 shows the result for a steel-PMMA layered medium subjected to a loading pulse of 0.2 μs duration. The direction of wave propagation is normal to the layers. The effective modulus theory was also used to model the same event. It is obvious that the present model gives much more accurate solution than the effective modulus theory.

The present method was also applied to solve the dynamic response of fiber reinforced composite materials subjected to transient loading of 0.2 μs duration. The result is compared in Figure 9 with the results from the effective modulus theory and

FEA using the ABAQUS explicit code. Again the present model yields much more accurate results than the effective modulus theory.

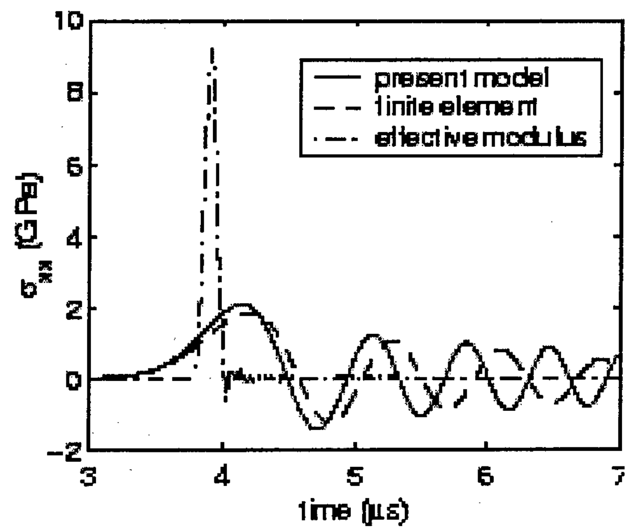


Figure 8 Stress histories in steel/PMMA layered medium. The duration of the triangular transient loading is $\Delta t = 0.2(\mu s)$.

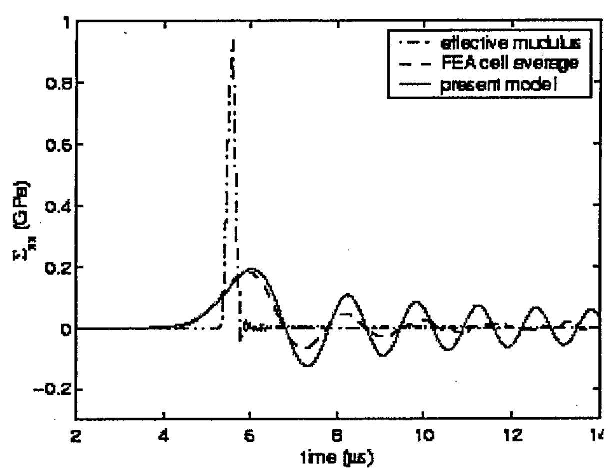


Figure 9 Stress histories in E-glass/epoxy fibrous composite. The duration of the triangular transient loading is $\Delta t = 0.2(\mu s)$.

3.3 Advanced Experimental and Computational Methods

3.3.1 Nonlinear Finite Element Code

The nonlinear finite element code `NonStaD` was developed to model problems involving the impact and fracturing of ceramics. Specific features added for fracturing:

- Cohesive modeling of the fracturing process,
- Different cohesive properties for bulk and interface behavior.
- Degradation and erosion of ductile layers.

- Multiple body contact & impact.

3.3.2 New Experimental Methods

Experimental problems by their nature are only partially specified. The inverse methods program `Wavelet` was developed to allow experimental data to be incorporated with a general finite element analysis so that problems are completely specified. This creates many possibilities of totally new types of experimentations. Some of the specific features are:

- It can be coupled to a general purpose FEM code and hence the type and complexity of problems solved are those usually handled by these FEM codes.
- The method can use either discrete multiple sensors (e.g., strain gages or accelerometers) or whole-field images (e.g., Moire or interferometry) as input data.
- It can determine multiple unknown force histories or multiple traction distributions.
- Only sub-domains of the structure/specimen need be analyzed.

Some of the new experimental designs investigated and verified are:

- A one-sided Hopkinson bar was designed to apply known high-frequency loadings to arbitrary specimens. This new arrangement is convenient, versatile, and accurate. The method was experimentally verified using strain gages and accelerometers.
- Material properties of gradient and layered materials were determined from surface measurements only. The method has been verified using synthetic data. The investigation allowed the identification of appropriate instrumentation for the experimental implementation.
- The dynamic cohesive properties of laminated materials were determined from a limited number of Moire photographs. The example problems using synthetic data had multiple crack branching and fragmentation. The appropriate instrumentation for the experimental implementation has been identified.

3.3.3 Parametric Study of Layered Materials

The FEM program `NonStaD` was used to investigate the damage tolerance of ceramic/aluminum layered composites. The study looked at the effect of interface bonding, boundary constraint, number and sequence of layers, with the controlling variable being the velocity of the projectile. A detailed history of the impact, peneration, cracking, and erosion can be produced, plus a history of the resistance to penetration. A typical set of results are shown in Figure 10. The constraining effect of the aluminum layer is identified as highly beneficial in giving damage tolerance to the bare ceramic material.

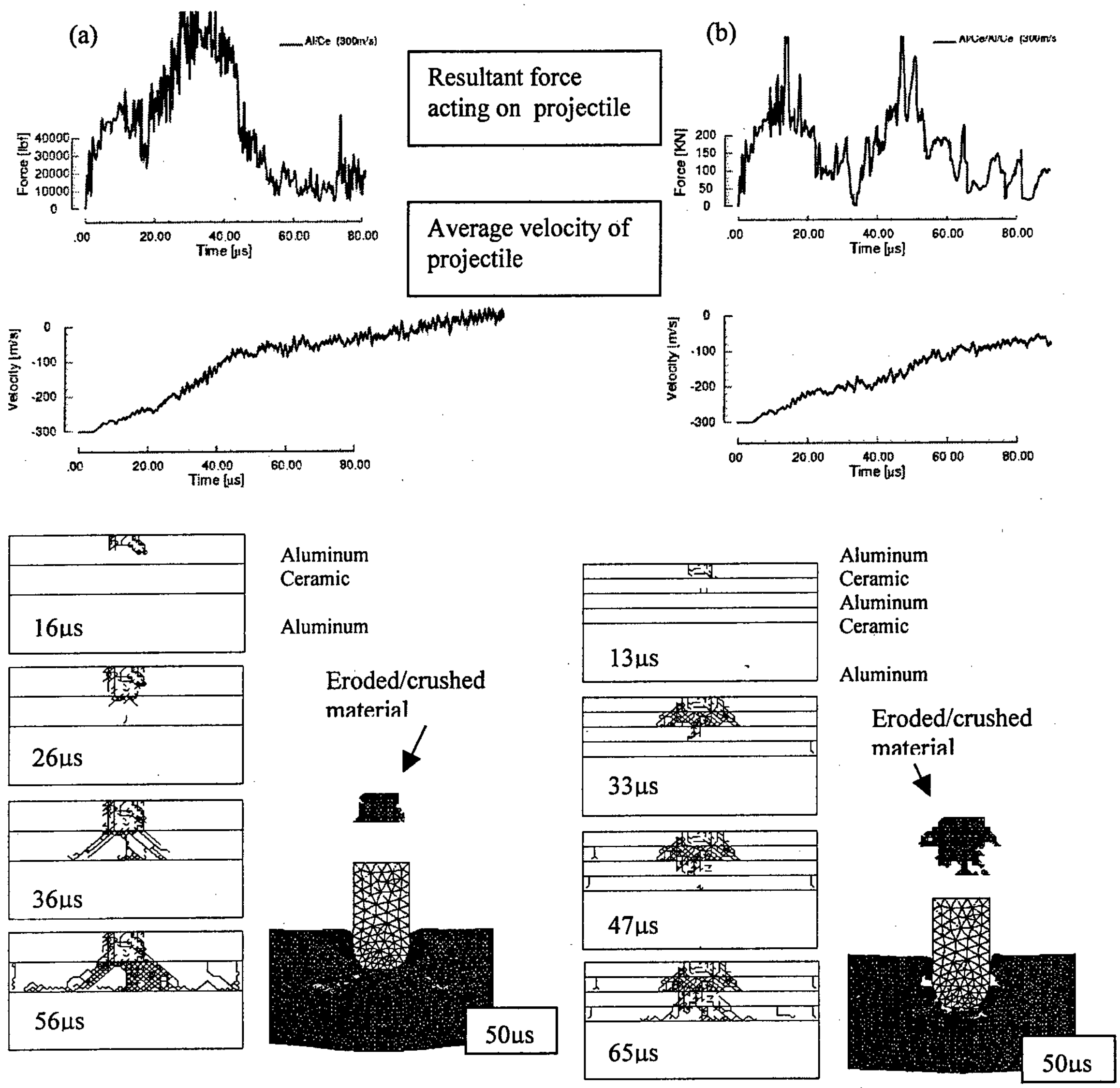


Figure 10: Evolution of damage of an aluminum/ceramic layered material impacted by a steel projectile traveling at 300m/s. Although the cracking in case (a) is more extensive than case (b), case (a) defeats the projectile sooner and has less penetration than case (b). This is because of the constraint effect of the aluminum layer.

3.4 Numerical Simulation of Penetration of High Hardness (Rc~61) Tool Steel Penetrators

Numerical simulation of penetration into aluminum was carried out using the EPIC finite element code. Johnson-Cook material models for the tool steel penetrator (R_c=50) and aluminum were used. It was found that extremely high yield strength of 3 GPa (two times that for R_c=50 tool steel) was required to match the measured DOP. The lack of constitutive model data for hard tool steel is the major reason for the discrepancy between the numerical simulation and the present experiments. Therefore, we developed the material model for tool steel by in collaboration with the ARL personnel (D. Grove).

Johnson-Cook material model constants for the hard tool steel (R_c=61) were determined by performing quasi-static, high strain rate (SHB), and bar impact experiments. These results will be of great interest to the ballistic community since APM2 (Armor Piercing) bullets, extensively used for armor testing, have high hard steel cores.

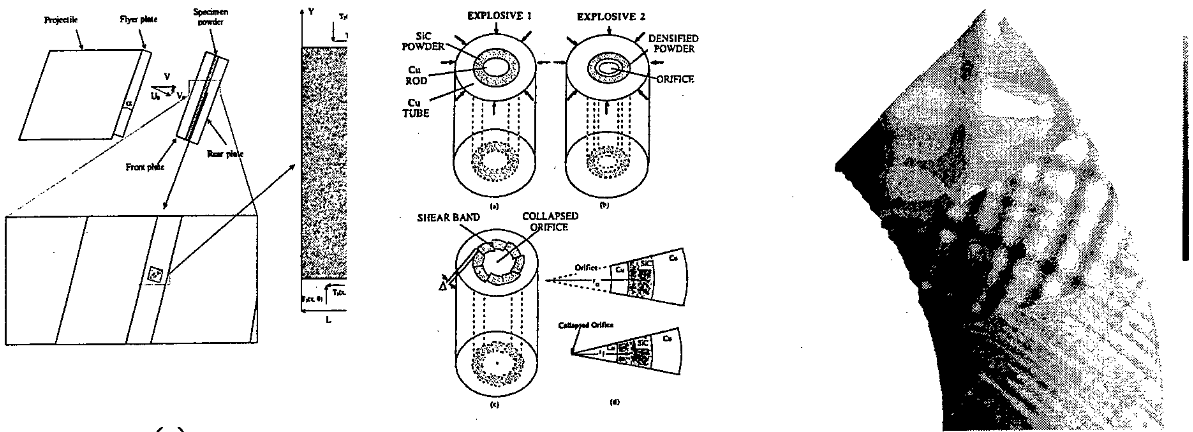
Material response of high hard tool steel was found to be brittle in tension and ductile in compression. Additionally, the yield strength was found to be 3.0 GPa in compression and 2.5 GPa in tension. These data were used to develop a failure model for the material. The model was incorporated in a finite element code and numerical simulations of penetration of hard steel projectiles and multi-component projectiles, such as the APM2 against metal and metal/ceramic targets were carried out. Three configurations are investigated. The first involves impacting a hard steel hemi-nosed rod against a 6061 semi-infinite aluminum target. The second, is the APM2 projectile against a semi-infinite aluminum target. The third, is a layered target in which a ceramic tile has been bonded to an aluminum substrate. We find that inclusion of the proposed failure model for the steel yield agreement to within 5 % between the computations and the experiments. When the computations were performed without the failure model, depth of penetration was over predicted by the code.

3.5 Experiments and Modeling of Ballistic Penetration in Multilayered Ceramic Targets

One of the main objectives of this project was the investigation of failure mechanisms in multi-layered ceramic targets. The findings reported by Hauver and co-workers, and Bless and co-workers, concerning the design of ceramic targets to achieve interface defeat were further examined by extending their experimental technique to include in-material stress measurements and real time free surface velocity histories, Espinosa, Brar et al., 2000. Examination of the post-shot multi-layered ceramic targets revealed complete and partial interface defeat of long rod tungsten heavy alloy penetrators. Targets with extra stiffness, on account of weld and larger bottom plate thickness, achieved complete defeat of the penetrator. These findings proved that the role of structural design was more significant than the ceramic type. TiB_2 proved to be a better material than Al_2O_3, in the sense it that required less confinement. Both materials achieved interface defeat, but the extent of fragmentation was quite different.

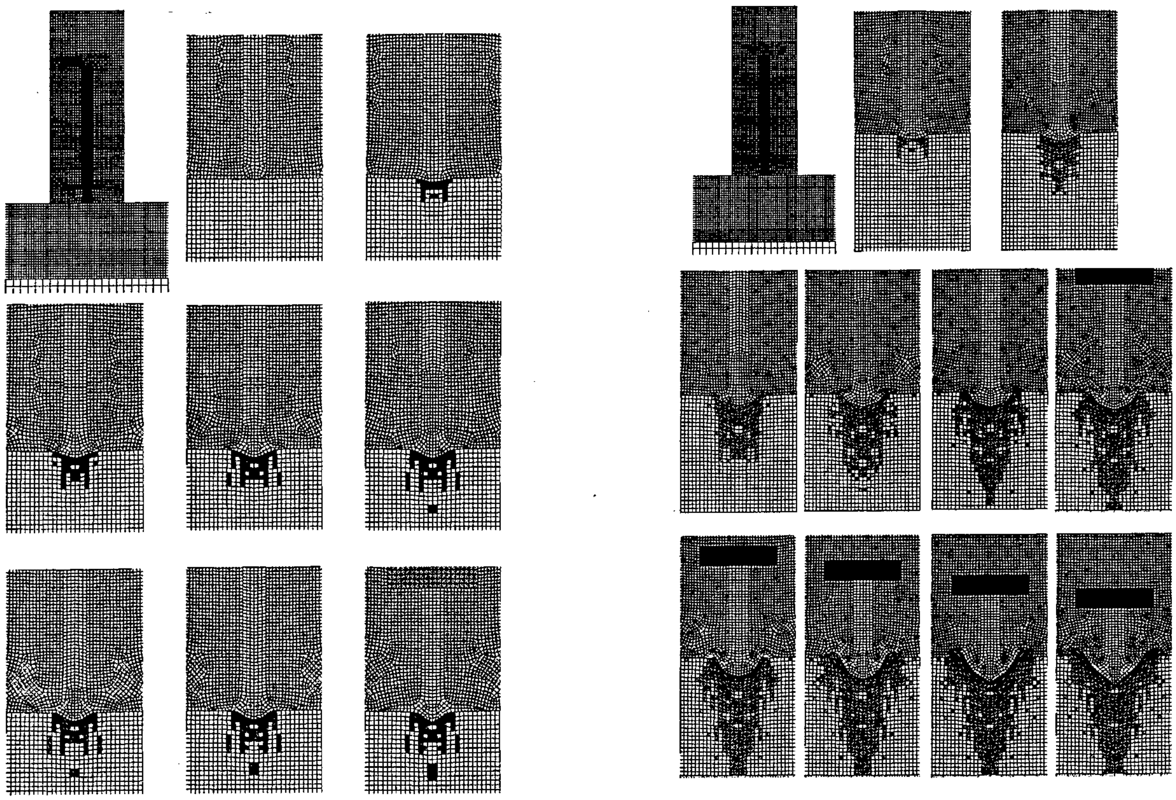
The next challenge was to develop a model that could provide ballistic penetration predictive capabilities. In order to achieve this goal, two distinct models, a multiple-plane microcracking model developed by Espinosa, 1995 and a granular model, originally developed by Anand and modified by Espinosa and Gailly, 2001, were combined in a consistent fashion. The idea was to develop a continuum model capable of capturing crack initiation and propagation as well as transition to a pulverized ceramic. Each model was independently calibrated in each regime. The MPM model was calibrated through plate and rod on rod impact experiments, Espinosa and Brar, 1995, Espinosa et al., 1998, while the granular model parameters were identified through simulation of pressure-shear impact of ceramic powders and cylinder collapse of ceramic powders experiments, Espinosa and Gailly, 2001, see Fig. 11. These simulations were able to capture for the first time features such as shear localization and dilation/consolidation. The combined model, with a fixed set of parameters, was then employed to simulate ballistic

experiments performed by Malaise et al., 2000. Not only was interface defeat predicted by calculation, but also the transition to penetration (see Fig. 12), with increasing impact velocity, was captured by the simulations, Gailly and Espinosa 2001.



(a) (b) (c)

Figure 11 (a) Pressure-shear plate impact configuration for testing ceramic powders and computational cell, (b) Experimental steps for densification and deformation of granular ceramic, Nesterenko et al., 1998, (c) Simulation of cylinder collapse experiment for fine 0.4 μm average particle size SiC powder. Contours of plastic strain due to the distortion mechanism, $\gamma^{(1)}$. The model captures shear bands when a fine mesh is utilized.



(a) (b)

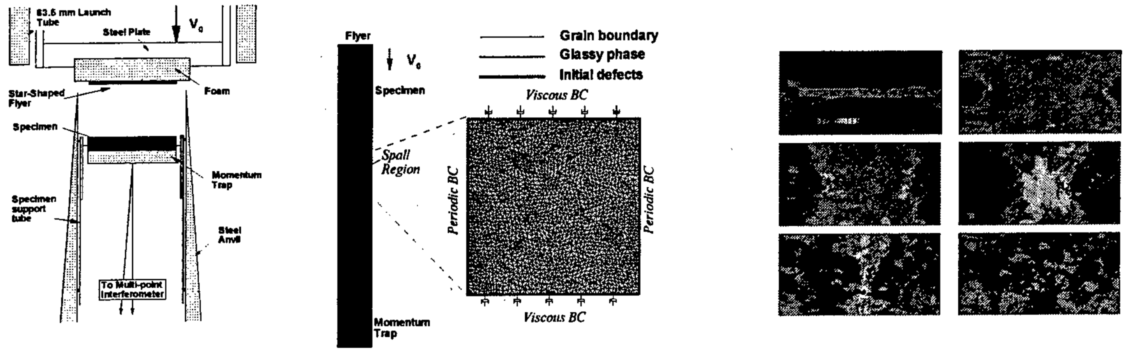
Figure 12. (a) Simulation of the Interface Defeat configuration, $V_{impact} = 1450$ m/s, (b) Simulation of the Interface Defeat configuration, $V_{impact}=1900$ m/s.

3.6 Grain Level Modeling of Impact Soft-Recovery Experiments

Characterization of material behavior under well-defined loading and boundary conditions at high strain rates, were performed to gain insight into the failure of materials under various multiaxial loading conditions. Specimen recovery was obtained to assess failure modes by means of microscopy studies. Information on crack initiation and its kinetics was obtained through interferometrically measured velocity histories, Espinosa et al., 1997, 1998, 2000. The concept of pressure-shear impact with soft-recovery of brittle materials was established and its limitation identified. In parallel with this effort, computational models were developed to account for multi-body contact, finite kinematics of deforming bodies, thermo-mechanical coupling and mesh adaptivity, Espinosa et al., 1998. Finite deformation models for ductile materials were developed using viscoplastic laws including hardening and thermal softening. To capture discrete fragmentation in brittle solids, cohesive fracture laws were embedded in an extended finite element formulation (X-FEM), Espinosa et al., 1998.

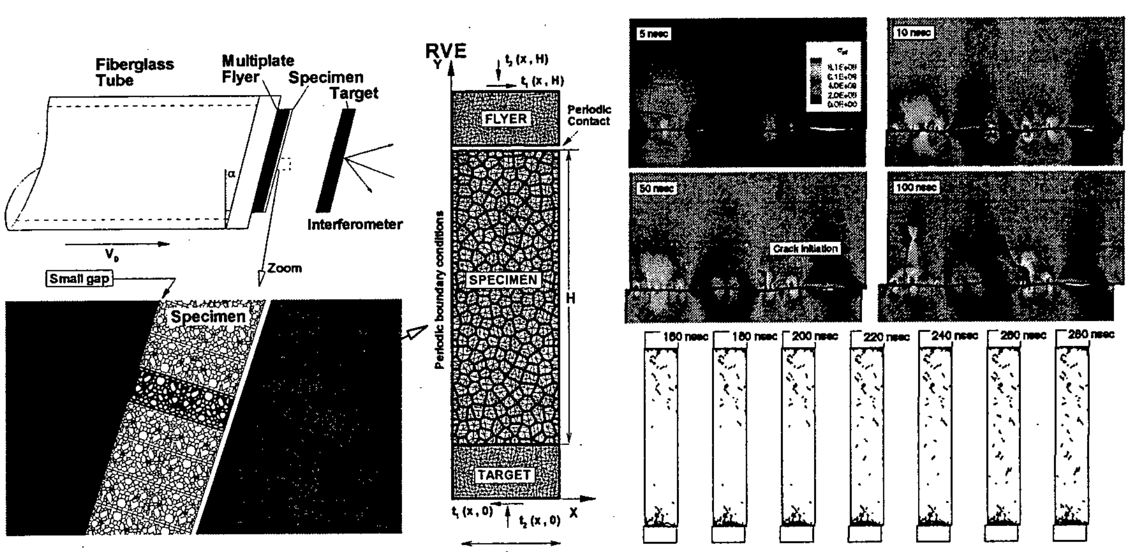
In the past, only continuum models were used to describe material behavior. With advances in computational capabilities, massively parallel computers, utilization of more sophisticated models become feasible. Using a parallel version (MPI) of the developed X-FEM code, representative volume elements (RVE) of ceramic microstructures were analyzed for both normal impact soft-recovery experiments and pressure-shear soft recovery experiments. The numerical simulations were based on a 2-D stochastic finite element analysis. The model incorporated a cohesive law to capture microcrack initiation, propagation and coalescence, as well as crack interaction and branching, as a natural outcome of the calculated material response. The stochasticity of the microfracture was modeled by introducing a Weibull distribution of interfacial strength and toughness at grain boundaries. This model accounted for randomness in grain orientation, and the existence of chemical impurities and glassy phase at grain boundaries. Representative volume elements (RVE) of ceramic microstructure with different grain size and shape distributions were considered to account for features observed in real microstructures (Fig. 13). Normal plate impact velocity histories were used not only to identify model parameters, but also to determine under what conditions the model captured failure mechanisms experimentally observed. The analyses showed that in order to capture damage kinetics a particular distribution of grain boundary strength and detailed modeling of grain morphology are required. *Simulated microcrack patterns and velocity histories have been found to be in a good agreement with the experimental observations only when the right grain morphology and model parameters were chosen.* It has been found that the addition of rate effects to the cohesive model resulted in microcrack diffusion not observed experimentally, Zavattieri and Espinosa, 2001a.

Grain level micromechanical analyses of ceramic microstructures subjected to dynamic compression-shear loading conditions were also performed. The investigation consisted of a combined experimental/numerical approach in which bulk and surface material properties were examined by means of pressure-shear impact experiments. The model incorporated a cohesive law to capture microcrack initiation, propagation and coalescence. Surface roughness was also included in the analysis to capture the time dependent frictional behavior of the various interfaces. The ceramic model accounted for randomness in grain orientation, the existence of chemical impurities and glassy phase at grain boundaries, thermo-elastic anisotropy, visco-plasticity and surface characteristics. Model parameters identified in the simulation of normal impact were employed. The model for the steel anvil plates accounted for finite deformation visco-plasticity, thermal softening and strain hardening. Representative volume elements (RVE) of ceramic microstructure and anvil plates were considered to account for features observed in the experiments. Pressure-shear impact velocity histories were used not only to identify inelasticity, but also to determine dominant failure modes. Simulated velocity histories have been found to be in a good agreement with the experimental observations when bulk *and* surface features were included in the analysis. *It was demonstrated that the velocity histories measured in pressure-shear experiments performed on hard ceramics provide mostly information on the time dependent frictional behavior of the specimen-anvil interfaces.* Bulk ceramic properties did not affect the velocity history in any significant way. A methodology for bridging between micro- and macro-scales was achieved by using the developed model, Zavattieri and Espinosa, 2001b.



(a) (b) (c)

Figure 13. (a) Schematic of the experimental configuration, and (b) computational cell considered in the analysis including a description of microcracking at grain boundaries using interface elements. (c) Evolution of the crack pattern and y component of the stress for one of the cases.

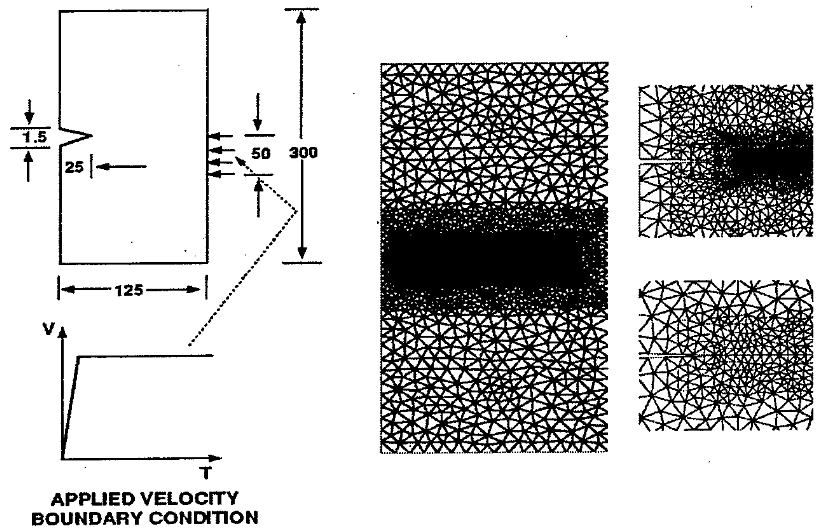


(b)

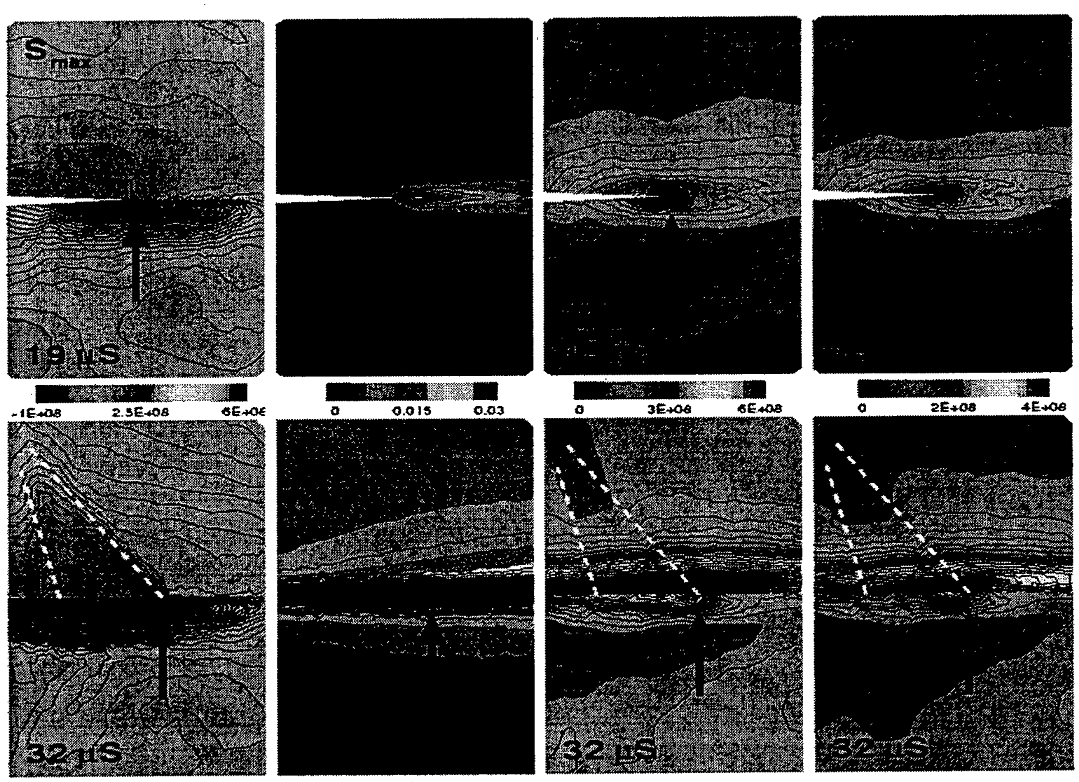
Figure 14. (a) Schematics of the experimental configuration and the RVE (b) Evolution of the crack pattern for full scale simulation.

3.7 Intersonic Crack Propagation in Bimaterials and Fiber Reinforced Composites

Espinosa and his students studied the high-strain-rate behavior of fiber composite materials through pressure-shear soft-recovery experiments (Espinosa et al., 1997) and ballistic penetration experiments with real time penetrator tail velocity history measurement (Espinosa et al., 1998). A 3-D finite deformation anisotropic viscoplasticity model was developed to capture ply inelasticity in fiber composites. This model was combined with the X-FEM software to simulate ballistic penetration experiments performed on fiber composites (Espinosa et al., 2001). Simultaneously, exciting activities in the area of dynamic crack propagation in bi-material interfaces developed. It was experimentally shown that cracks could propagate intersonically, i.e., crack speed in excess to the Rayleigh wave speed in the material, in some bi-material interfaces. The question was if such behavior could be expected in the case of fiber composites. And if so, what would be the criterion for predicting intersonic crack propagation in unidirectional Carbon/Epoxy composite. Espinosa and co-workers addressed this question by performing numerical simulations of rod on plate impact experiments (see Fig. 15a) using the computational tools implemented in the X-FEM software and the finite deformation anisotropic visco-plastic model developed to describe the constitutive response of fiber composites. Embedded zero thickness interface elements along the possible crack path were used to simulate crack extension. An irreversible mixed mode cohesive law was used to describe the evolution of tensile and shear tractions as a function of corresponding displacement jumps. The compressive response, behind the crack tip, was modeled using a contact algorithm. Crack propagation was achieved through consecutive failure of interface elements as an outcome of the calculations. The dynamic failure phenomenon was studied in terms of time for crack extension, crack speed, mode mixity associated with the failure of interface elements, effective plastic strain at the crack tip and path independent dynamic J integral. To verify the model, analyses were first carried out for dynamic crack propagation along bi-material interfaces. The results agreed very well with literature data. Detailed analyses were then carried out for a pre-notched unidirectional Carbon/Epoxy composite material (Fig. 15a). The impact velocity in the analyses was an imposed velocity over an assumed impact diameter and remained constant throughout the analysis. Analyses were carried out at impact velocities of 5, 10, 20, 30 and 40 m/s, assuming the crack wake was frictionless. Moreover, analyses at impact velocities of 30 and 40 m/s were also carried out with a friction coefficient of 0.5, 1.0, 5.0, and 10.0 along the crack surfaces. *The analyses unequivocally established steady state intersonic crack propagation in the investigated fiber reinforced composite material* (Fig. 15b). Intersonic crack propagation for the impact velocity of 40 m/s was 3.9 times the shear wave speed and 83% of the longitudinal wave speed. Rosakis and co-workers at Caltech later confirmed these findings. The simulations also showed that the friction coefficient does not have appreciable effect on the maximum crack speed in the steady state regime, but smears the mach wave discontinuity behind the crack tip. *The analyses showed that the dynamic J integral computed at near field contours are path independent and can be addopted as a parameter for characterizing intersonic crack propagation.* Contrary to other models, J did not approach zero when the crack approached intersonic speeds, Dwivedi and Espinosa, 2001.



(a)



(b)

Figure 15. (a) Problem definition and mesh used in the analyses; (b) Crack tip state parameters, maximum principal stress S_{max}, effective plastic strain ε^p, effective stress S_{eff} and principal shear stress S_{12} at the instant of crack initiation and at maximum crack velocity for imposed velocity of 30 m/s.

3.8 Novel Experimental Techniques with High-Speed Photography and Full Field Measurements

Espinosa and his students developed a stored energy Kolsky bar apparatus for compression-shear high strain rate testing of materials with specimen recovery. The apparatus was used to investigate dynamic friction, Espinosa et al, 2000a and b, dynamic torsion of nano-coatings, Espinosa et al, 2000c, and dynamic fracture of ceramics, Espinosa and Barthelat, 2001.

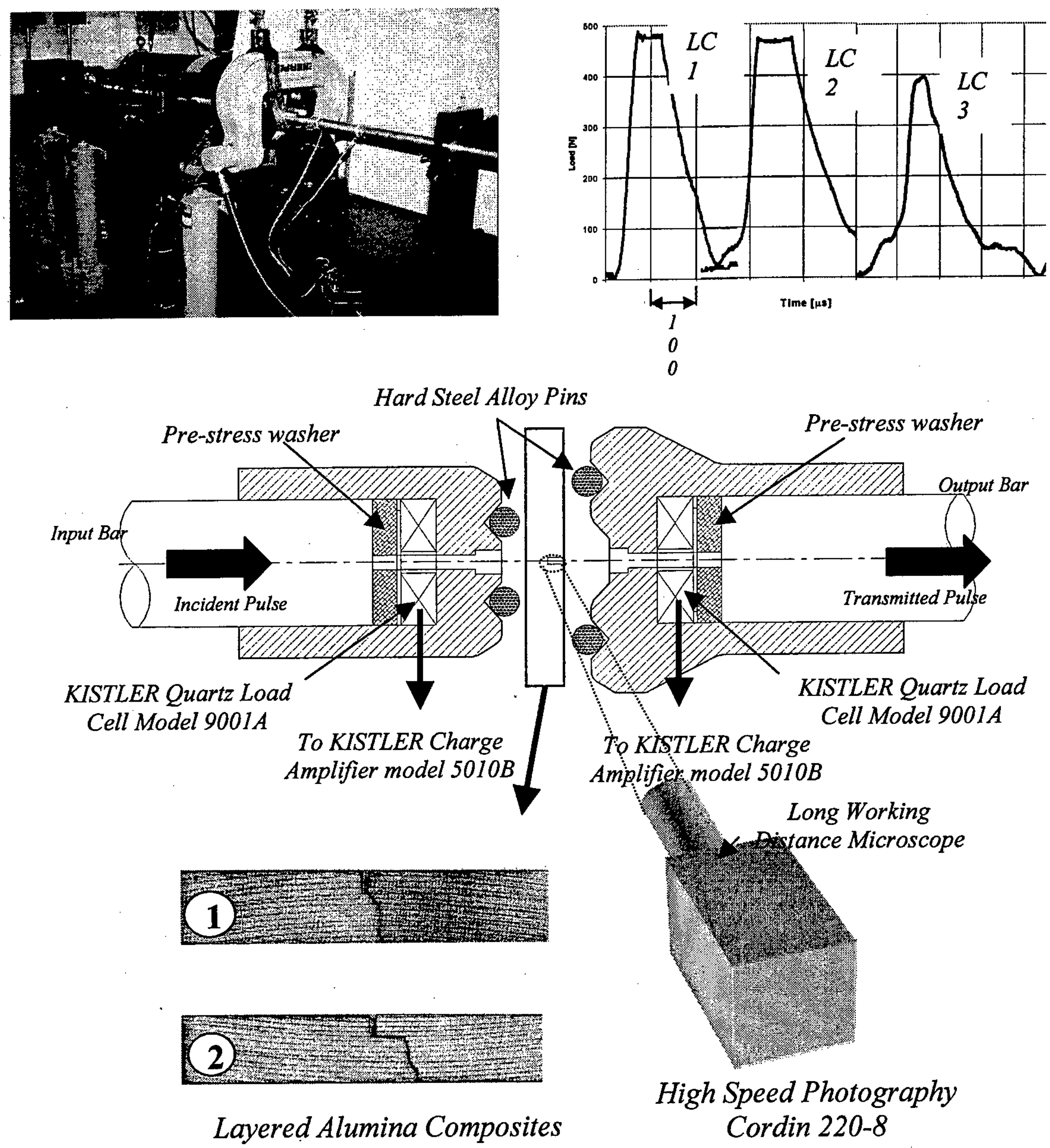


Figure 16: Photograph of designed and manufactured Kolsky bar (top left); load histories measured for multilayered ceramic samples (top right); set-up for dynamic fracture experiments with high-speed photography (bottom).

The apparatus, Fig. 16a, is composed of two 1-inch (25.4 mm) 7075-T6 aluminum alloy bars. The so-called incident, or input bar, is 90.5 in (2.3 m) long and the so-called transmission, or output bar, is 75 in (1.9 m) long. Each bar is supported by a series of re-circulating fixed-alignment ball bearings (*INA KBZ16PP*) minimizing the friction resistance on the supports and allowing the bar to rotate and translate freely in both directions. The compression/tension and shear loading pulses are produced by the sudden release of the stored elastic energy. This requires both torsional and compression/tension actuators. The axial part of the elastic energy is produced by means of a hydraulic double acting actuator (*Enerpac RD 166*), which applies a compressive or tensile load at one end of the incident bar. Its capacity is 35 kip (*150 kN*). The torsional part of the elastic energy is achieved by means of a hydraulic rotary actuator (*Flo-Tork 15000-180-AICB-ST-MS2-RKH-N*) located along the incident bar. It is connected to the bar by a 3/8" steel key. Its capacity is 15,000 lb·in. (*1700 N·m*). The sudden release of the stored energy is achieved using a clamp positioned between the rotary actuator and the specimen. The design of the clamp is crucial for good results. The clamp must be able to hold the desired torque and compression/tension force without slippage, and release the stored energy rapidly enough to produce a sharp-fronted stress pulse traveling towards the specimen.

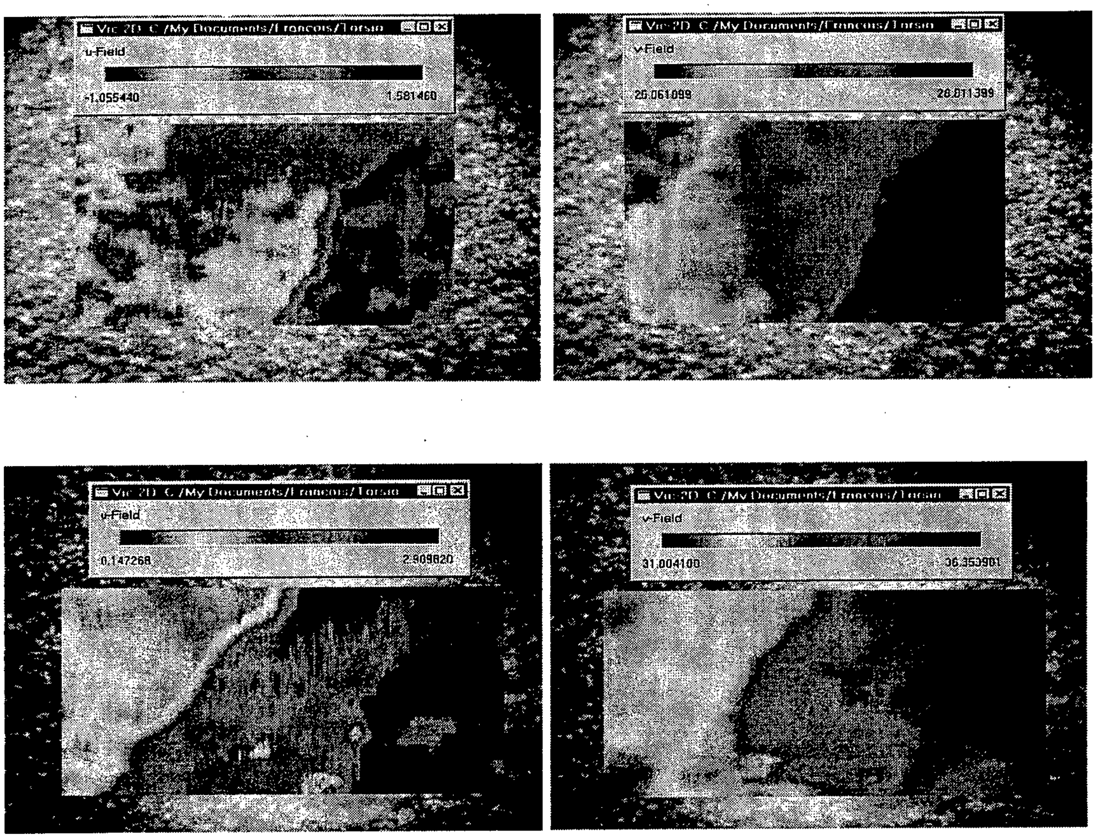


Figure 17 : Contours of horizontal and vertical displacement fields as obtained by image correlation of speckle patterns on sample surface.

The Kolsky bar was also used to conduct dynamic fracture studies of ceramics, see Fig. 16. In these experiments, real time incident and transmitted loads were measured with

quartz crystals and high frequency amplifiers (Kistler C78497). Crack tip deformation was identified employing high-speed photography (Cordin Model 220-8 Camera system and Model K2 long distance microscope) and a speckle cross-correlation technique. The correlation was performed using the software VIC-2D 2.0 (Correlated Solutions, 1998). Excellent resolution was found when the speckle size and illumination conditions were properly chosen. Fig. 17 shows displacement contours in which displacement jumps, due to the presence of microcracks, are clearly observed even before the microcracks are visible on the surface of the sample. The experiments showed the fracture toughness of the layered alumina ceramic is not rate dependent and that the failure mode remains the same as in quasi-static fracture.

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